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New times of maximum of CY Aquarii

T. Tuvikene[1,2], C. Sterken[1], E. Brogt[3,4], D. Cont[5], A. Henden[6], C. Papadaki[1], I. Volkov[7] and C. Wiedemair[5]

[1] Vrije Universiteit Brussel, 1050 Brussels, Belgium
[2] Tartu Observatory, 61602 Tõravere, Estonia
[3] University of Canterbury, Christchurch 8140, New Zealand
[4] Steward Observatory, Tucson, AZ 85721, USA
[5] Realgymnasium Bruneck, 39031 Bruneck, Italy
[6] AAVSO, Cambridge, MA 02138, USA
[7] Sternberg Astronomical Institute, Moscow University, Russia

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Abstract

We present a collection of 102 new times of maximum of the SX Phoenicis star CY Aquarii. These times, together with 20 times of maximum taken from the literature, lead to a new local linear ephemeris for 2003–2009 with a formally slightly shorter period than the one for 1996–2002. It will require at least another half decade of additional monitoring before any significant update to any model can be considered. Such monitoring should preferably occur at regular intervals, be done in a consistent photometric band, and at high time resolution.

Keywords: technique: photometric – stars: CY Aqr

1 Introduction

CY Aquarii (BD +0°4900) is a short-period (87.9 min) large-amplitude ($0\overset{\mathrm{m}}{.}71$ in V) SX Phoenicis star. Since the discovery of its variability in 1934, this pulsating star has been extensively observed, and several investigations of its changing pulsation period using the $O-C$ diagram have been published. The latest substantial study of the long-term period change of CY Aqr (Fu & Sterken, 2003) listed 23 new times of maximum (hereafter denoted as $T_{\max}$), and from an analysis of the $O-C$ diagram of all available $T_{\max}$, these authors derived an updated value of the pulsation period of

$0\overset{d}{.}061038394 \pm 0\overset{d}{.}000000006$. A linear period change combined with the light-time effect in a highly-eccentric orbit led them to a possible solution involving a highly-eccentric ($e = 0.77 \pm 0.01$) orbit with period $P_{\rm orb} = 52\overset{y}{.}5 \pm 0\overset{y}{.}3$. Their Fig. 3 indicates that by the end of 2002, the $O-C$ curve was approaching a maximum, so that the subsequent decade could possibly confirm the binary model.

This paper presents a collection of $T_{\rm max}$ obtained since the last maximum used by Fu & Sterken (2003), in addition to 6 timings obtained in 1998–2000. These times were derived from new photometric observations as described in Section 2, together with some $T_{\rm max}$ taken directly from the literature.

2 Observations and data reduction

The bulk of the data discussed in this Section were obtained through CCD imaging at more than half a dozen observatories worldwide. Some light curves were also acquired through differential photomultiplier-based photometry. Table 1 gives the journal of observations.

Table 1: Journal of photometric observations: JD, observatory site, number of nights with at least one $T_{\rm max}$, photometric band and number of measurements. "Red." refers to the initials of the author who carried out the data reduction.

JD−2400000	Site	N	Band	Data	Observer	Red.	Data file
51107.62–51195.60	USNO	4	UVI_c	290	AH	AH	`usno.dat`
51806.74–51806.82	TASS	1	VI_c	82	AH	AH	`tass.dat`
53249.50–53250.58	SKO	2	–	794	CP	TT	`osk.dat`
53286.47–53292.46	OHL	4	–	806	CP	TT	`ohl.dat`
53304.27–53306.27	MLO	3	V	278	CS	CS	`mlo.dat`
53304.27–53311.40	SAI	6	–	911	IV	TT	`sai.dat`
53556.79–53565.93	OCA	6	B	1910	TT	TT	`oca-b.dat`
53561.73–53561.84	OCA	1	–	16057	TT	TT	`oca-fast.dat`
53612.92–53613.78	MDM	2	B	84	EB	TT	`mdm.dat`
53682.34–53689.34	SAAO	4	V	322	TT	TT	`saao.dat`
54729.29–54829.27	RGB	9	–	4972	DC, CW	TT	`rgb.dat`

Observer code: EB = E. Brogt; DC = D. Cont; AH = A. Henden; CP = C. Papadaki; CS = C. Sterken; TT = T. Tuvikene; IV = I. Volkov; CW = C. Wiedemair.

Except when stated otherwise, CCD magnitudes were extracted by means of aperture photometry, using routines in the IDL Astronomy User's Library[1] in a workflow as described by Tuvikene (2010). Aperture sizes were scaled with the full

[1] `http://idlastro.gsfc.nasa.gov/`

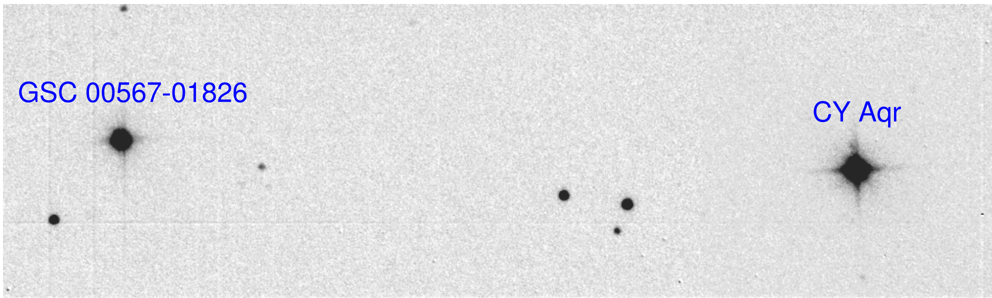

Figure 1: Frame of CY Aqr region obtained with the Danish 1.5-m telescope in September 2002. North is up and East is left, field of view is $6.'6 \times 2.'0$.

width at half maximum (FWHM) of stellar images, and an aperture radius of (1.6, 2.0, or 2.5)×FWHM was used throughout each data set, see also Tuvikene et al. (2008) and Tuvikene & Sterken (2010). Exceptions to this rule are those data sets where we used the magnitudes extracted by the cited authors. Deviations from the above-mentioned procedures are indicated in the following subsections.

Differential light curves of CY Aqr were obtained by using GSC 00567–01826 as a comparison star, see Fig. 1 for a finding chart.

2.1 USNO

CCD frames were acquired with the USNO-Flagstaff 1.0-m telescope on October 21 and 29, 1998 (V and I_c band, respectively) and on December 15, 1998 and January 17, 1999 (U band). The field of view was $11.'3 \times 11.'3$, with pixel scale of $0.''6763$ pixel^{-1} using a SITe/Tektronix thinned, back-illuminated 1024×1024 CCD. Aperture photometry was used with aperture diameter of 14 arcsec.

2.2 TASS

This is a simultaneous V/Ic set from September 19, 2000, using the USNO TASS Sky Survey camera. TASS uses dual 10-cm telescope apertures, with a Loral front-illuminated 2k×2k CCD for each telescope. The final image scale is $7.''5$ pixel^{-1}. Each exposure is 120 seconds long, and the resultant images were dark-subtracted and flat-fielded. Aperture photometry was used, with an aperture set to 30 arcsec diameter to match the pixel scale and seeing with the system.

2.3 Skinakas Observatory

Observations with the 1.3-m Ritchey-Chrétien telescope were made at Skinakas Observatory (SKO, Greece) on August 31 and September 1, 2004. The field of view (FOV) was $8.'5 \times 8.'5$ on a 1024×1024 pixel SITe CCD camera.

2.4 Observatorium Hoher List

On October 7–13, 2004, CCD frames were acquired at Observatorium Hoher List (OHL) in Germany, using the 1-m Cassegrain-Nasmyth telescope with the 2048×2048, 15-μm pixel HoLiCam CCD camera with a two-sided read-out. The focal reducer was used, the effective FOV was $14\rlap{.}'1 \times 14\rlap{.}'1$.

2.5 Mount Laguna Observatory

In September 2004 the Smith 24-inch telescope at Mount Laguna Observatory (MLO, San Diego State University, CA) was used. The telescope is an $f/20$ Cassegrain reflector equipped with a pulse-counting photoelectric photometer employing a thermoelectrically cooled Hamamatsu R943-02 GaAs photomultiplier tube.

The observations were carried out in a continuous sequence $C, P, S, C, P, S, C, \ldots,$ where P is CY Aqr, S the sky background, and C is the $V \approx 11.7$ comparison star about 5 arcmin East of P (see Fig. 1). As a rule, each observation consisted of at least five 10-s integrations, but during the phase of maximum light, P consisted of 2–3 series of such integrations. All measurements were taken through a standard Johnson V filter. The counts were corrected for dead time and for sky background contribution, the resulting instrumental magnitudes were corrected for atmospheric extinction, and then differential magnitudes with respect to C were formed. No transformation to the standard Johnson system was attempted.

Sky conditions were photometric. The combination of manual operation and small aperture yielded a data density of 5–7 measurements during a time interval of 15 minutes centered on the time of maximum, which is close to the lower limit for a reliable determination of $T_{\max}$.

2.6 Crimean Laboratory of the Sternberg Astronomical Institute

In October–November 2004 observations were made at the Sternberg Astronomical Institute Crimean Station (SAI). The following setups were used: on October 25 the Zeiss 60-cm Cassegrain telescope equipped with an Apogee-7 camera, and on October 27–30 and November 1, the Maksutov 50-cm telescope with a Pictor 416 CCD camera. Some nights were partially clouded. No adequate flat-field exposures could be collected, hence all magnitudes were obtained from frames that were only corrected for dark.

2.7 Observatorio Cerro Armazones

The star was intensely observed with the 84-cm telescope at Observatorio Cerro Armazones (OCA), Chile during 6 nights in July 2005. An SBIG ST-9E CCD-camera with a 512×512 KAF 0261E chip with a field of view of $11\rlap{.}'6$ was used. Raw frames were calibrated using dark frames and twilight flat-field frames. Figure 2 shows a sample of light curves collected at OCA on JD 2453565.

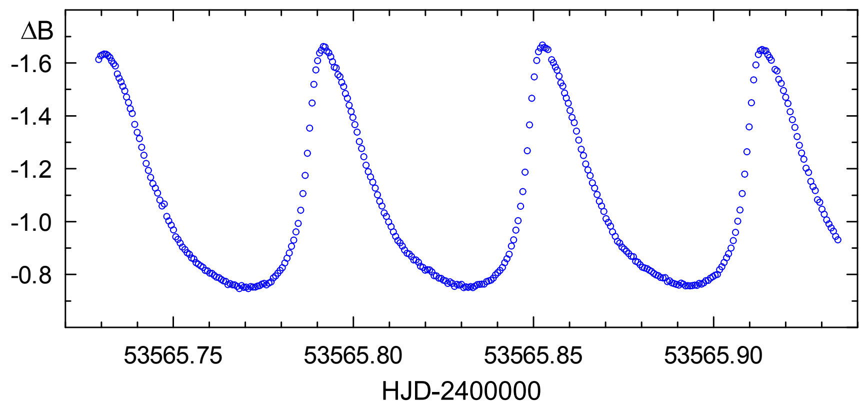

Figure 2: Sample of OCA B light curves.

In addition, on July 10, 2005 the 84-cm OCA telescope was used with the "Portable Occultation, Eclipse, and Transit Systems" (POETS) instrument, see Souza et al. (2006) and Gulbis et al. (2006). The system consisted of a high-speed Andor Ixon camera (512×512 pixels), instrument control computer, and a GPS receiver which provided accurate timing and triggered the exposures. Integration times were 1.74 ms less than the cycle time (0.5 s). A binning of 2×2 was used, resulting in a pixel scale of $2\farcs8$. No flat field nor bias frames were acquired, hence the resulting light curves were extracted from uncalibrated white-light CCD frames.

Figure 3 shows the differential magnitude of CY Aqr minus the comparison star, and also a binned light curve (bin width of 10 seconds, covering 20 frames). The light curves are quite regular, and are the best-covered light curves presented since the beginning of this star's observational history.

2.8 MDM Observatory

On October 30 and 31, 2007 the 2.4-m Hiltner telescope at the MDM Observatory, Arizona, USA, equipped with the 8k×8k Mosaic imager (FOV $23\farcm6 \times 23\farcm6$) was used.

2.9 South African Astronomical Observatory

In November 2005 the 1.0-m telescope at the South African Astronomical Observatory (SAAO), Sutherland, South Africa (STE4 CCD camera with 1024×1024 pixels, field of view $5\farcm3 \times 5\farcm3$, with V filter) was used. Raw frames were calibrated using bias and twilight flat-field frames.

2.10 Realgymnasium Bruneck

From September 19 to December 28, 2008, 14 partial nights of observations were obtained by a team of students from the Realgymnasium Bruneck (RGB, Südtirol,

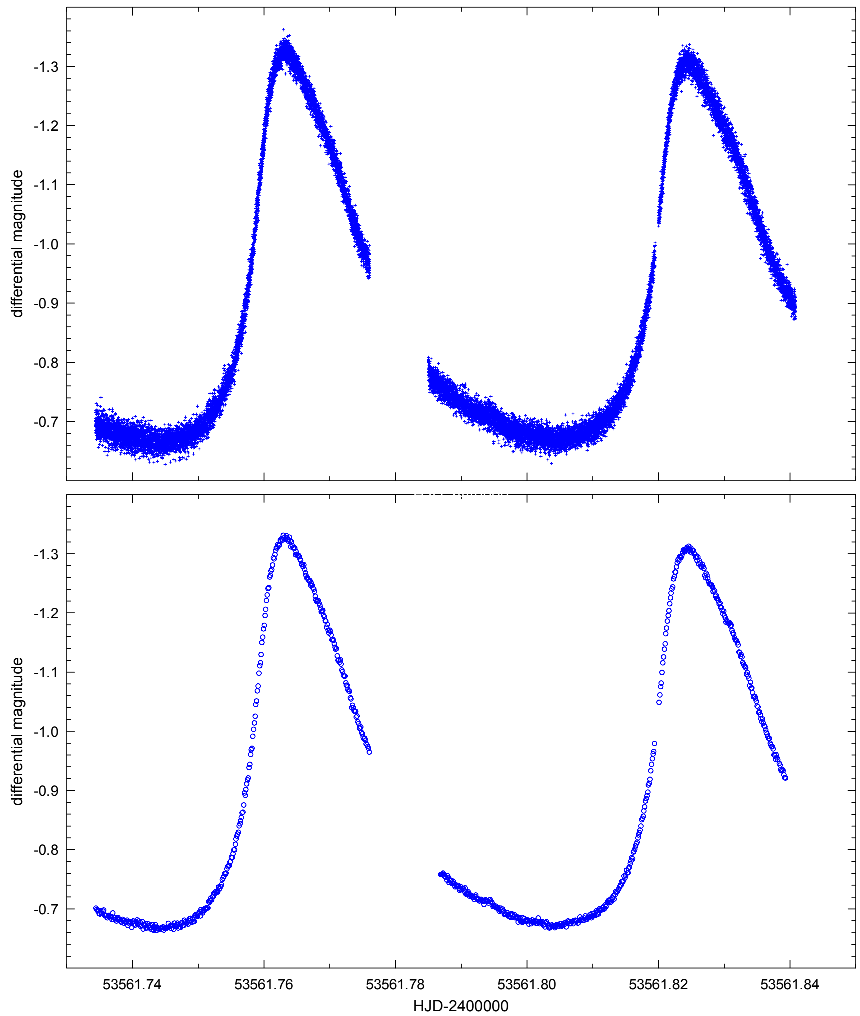

Figure 3: OCA high-resolution light curve, see Sect. 2.7. Top: raw light curve; Bottom: light curve binned in 10-second bins.

Italy) under the supervision of CW. A Meade LX200 telescope with an SBIG ST8-XME CCD camera was used on the college roof. Typical exposure time was 20 s, with 2×2 binning. The technical limitations of this rooftop equipment prevented the acquisition of valid flat-field frames, hence these CCD frames were dark-corrected only.

2.11 Miscellaneous sources

Published light curves and/or $T_{\max}$ were collected from various sources, viz.:

1. The American Association of Variable Star Observers (AAVSO) data archives

contains visual estimates since September 1968. From 2003 on, photoelectric observations of a dozen well-covered maxima have been added. The following light-curve data were used in this study (JD–2 400 000 followed by AAVSO observer code): 52931 (OAR), 53605 (ZRE), 53989 (PWM), 54008 (DKS), 54032 (DKS), 54734 (ATE), 54736 (ATE), 54738 (ATE), 54739 (ATE), 55085 (SJAR), 55114 (SJAR), and 55157 (SJAR).

2. One light curve was acquired by L. Barrera on July 1, 2003 at OCA with a 41-cm telescope, and its resulting $T_{\rm max} = 2452821.9182$ was published by Fu, Sterken & Barrera (2004).

3. Derekas et al. (2009), in a study of binarity and multiperiodicity in high-amplitude δ Scuti stars, list 11 new $T_{\rm max}$ obtained from V and I photometry.

4. Some isolated times of maximum are also listed by Hübscher et al. (2005), Bíró et al. (2006), Paschke (2007) and Paschke (2009).

5. Two new $T_{\rm max}$, viz 2453647.0339 and 2454007.0997 were acquired by Li et al. (2007). Three additional new maxima were given by these authors: one $T_{\rm max}$ derived from Figure 2 of Chen et al. (2003), and two maxima from AAVSO data. We have not retained the former maximum because the shape of the light curve in Fig. 2 of Chen et al. (2003) has a very irregular and atypical minimum and maximum, quite unlike Fig. 3. Moreover, these data are not of optimal quality because they were derived from square-aperture photometry in a very early version of the data-reduction pipeline software (Chen, 2010).

   We have not used the AAVSO-based $T_{\rm max}$ listed in Table 2 of Li et al. (2007), viz. 2454032.4915 and 2454032.5521, but we derived the $T_{\rm max}$ from the original data, as explained in Sect. 3.1, and we added the heliocentric correction.[2]

3 Times of maximum, new ephemeris and $O-C$ diagram

3.1 Times of maximum light

Times of maximum light were derived from visual inspection of the light curves with underlying running averages covering a time interval of ± 0.1 phase bins from the time of maximum. Since the set of light curves is quite heterogeneous with respect to data density and shape of the local maximum, we have established a scheme of weights (1–5) according to the criteria given in Table 2, in addition to applying a weight decrease by one unit whenever three estimates of the same maximum time based on the same data differed by more than $0\overset{\rm d}{.}002$. No weights were assigned to published $T_{\rm max}$, except for FSB2004 and L2007 for which light curves were available. All 122 $T_{\rm max}$ are listed in Table 3 (the electronic version is included as file `tmax.dat`). From comparison of derived maximum times in different photometric bands, we estimate

[2] The AAVSO database lists non-heliocentric JD.

that the mean error on one $T_{\max}$ is $\leq 0\overset{d}{.}0003$. Cycle numbers E were calculated using the ephemeris given by Fu, Sterken & Barrera (2004).

Table 2: Relative weights assigned to the $T_{\max}$ derived in this work.

Weight	Data density		Shape of maximum	Comment
1	very low		(ir)regular	
2	medium	+	irregular	
3	high	+	irregular	deviations from smoothness
4	medium	+	regular	
5	high	+	regular	smooth light curve

3.2 New ephemeris and resulting $O-C$ diagram

A linear least-squares fit of the 116 times of maximum in Table 3 obtained after the last $T_{\max}$ published by Fu & Sterken (2003) results in $P = 0\overset{d}{.}061038350 \pm 0\overset{d}{.}000000004$. Removing two outlying points with $O-C \approx 0\overset{d}{.}008$ (i.e. of the order of the heliocentric correction for the maxima labeled P2007) leads to essentially the same result: $P = 0\overset{d}{.}061038349 \pm 0\overset{d}{.}000000002$, though with improved accuracy.

Figure 4 shows the new $O-C$ points overplotted in Fig. 3 of Fu & Sterken (2003).

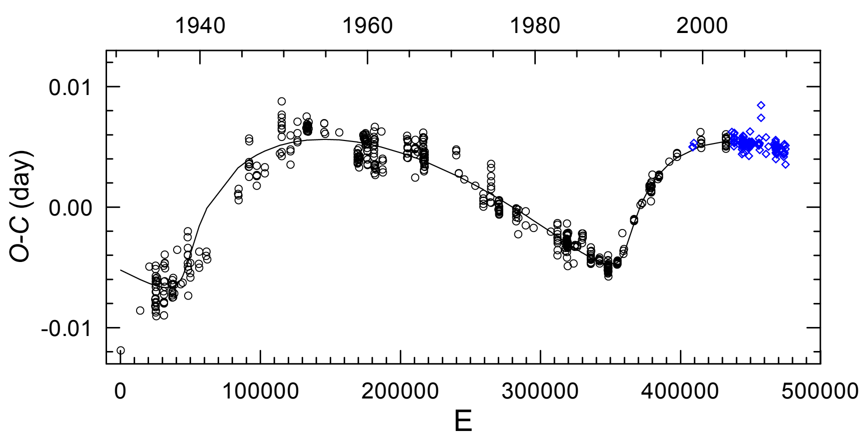

Figure 4: Resulting $O-C$ curve with respect to ephemeris (1) of Fu & Sterken (2003). Full line and $\circ$: light-time orbit solution and data from Fu & Sterken (2003), $\diamond$: from new $T_{\max}$ as listed in Table 3.

4 Conclusions

A set of 114 new times of maximum obtained since 2002 leads to a new local linear ephemeris for 2003–2009:

$$\begin{array}{rcrcl} T_{\max} & = & 2426159.512 & + & 0.061038349\,E \\ & & \pm 0.001 & & \pm 0.000000002. \end{array} \qquad (1)$$

The pulsation period in Eq. 1 is formally shorter than the one quoted in Table 3 of Fu & Sterken (2003) for 1996–2002 ($P = 0\overset{\mathrm{d}}{.}061038394 \pm 0\overset{\mathrm{d}}{.}000000006$), which does not mean that this result provides any evidence supporting the piecewise linear $O-C$ trend model. It will require at least another half decade of additional monitoring before any significant update to the presented model can be considered. Such monitoring should preferably occur at regular intervals (at least at the beginning and end of each observing season), be done in a consistent photometric band (preferably Johnson V) and at high time resolution in order to achieve data of high weight (4 or 5 in the scheme presented in Table 2).

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Table 3: Times of maximum light (HJD–2400000) of CY Aqr, weight W (from Table 2), cycle number E and photometric passband. Source refers to this paper and to references in the literature, viz. DKB2009: Derekas et al. (2009); FSB2004: Fu et al. (2004); HPW2005: Hübscher et al. (2005); BBC2006: Biró et al. (2006); LFZ2007: Li et al. (2007); P2007: Paschke (2007); P2009: Paschke (2009).

T_{max}	W	E	Source	Band	T_{max}	W	E	Source	Band
51107.6543	5	408729	Sect. 2.1	V	53566.5233	–	449013	BBC2006	V
51115.5893	5	408859	Sect. 2.1	I	53605.7721	4	449656	Sect. 2.11	V
51115.6503	4	408860	Sect. 2.1	I	53613.7080	1	449786	Sect. 2.8	B
51162.6502	1	409630	Sect. 2.1	U	53613.7678	2	449787	Sect. 2.8	B
51806.7891	1	420183	Sect. 2.2	I	53647.0339	5	450332	LFZ2007	V
51806.7892	1	420183	Sect. 2.2	V	53682.3752	4	450911	Sect. 2.9	V
52821.9182	3	436814	FSB2004	V	53683.2906	5	450926	Sect. 2.9	V
52903.4032	2	438149	Sect. 2.11	V	53683.3517	5	450927	Sect. 2.9	V
52920.9223	–	438436	DKB2009	V	53684.3285	5	450943	Sect. 2.9	V
52920.9827	–	438437	DKB2009	V	53688.3568	4	451009	Sect. 2.9	V
52921.0439	–	438438	DKB2009	V	53689.3337	4	451025	Sect. 2.9	V
52923.0587	–	438471	DKB2009	V	53989.3372	4	455940	Sect. 2.11	V
52926.9643	–	438535	DKB2009	V	53989.3980	3	455941	Sect. 2.11	V
52927.0258	–	438536	DKB2009	V	54007.0997	3	456231	LFZ2007	–
52930.3215	4	438590	Sect. 2.11	V	54008.7473	4	456258	Sect. 2.11	V
52931.2981	4	438606	Sect. 2.11	V	54032.4907	5	456647	Sect. 2.11	V
52931.3595	4	438607	Sect. 2.11	V	54032.5523	5	456648	Sect. 2.11	V
53249.5522	5	443820	Sect. 2.3	–	54092.2510	–	457626	P2007	V
53250.5287	5	443836	Sect. 2.3	–	54092.3110	–	457627	P2007	V
53254.9840	1	443909	Sect. 2.5	V	54307.5293	–	461153	DKB2009	I
53256.3278	–	443931	HPW2005	V	54308.5073	–	461169	DKB2009	I
53256.3883	–	443932	HPW2005	V	54410.5627	1	462841	Sect. 2.9	V
53256.8758	1	443940	Sect. 2.5	V	54671.5630	–	467117	P2009	V
53256.9374	1	443941	Sect. 2.5	V	54709.4677	3	467738	Sect. 2.9	V
53286.4191	5	444424	Sect. 2.4	–	54729.3056	3	468063	Sect. 2.10	–
53289.2884	2	444471	Sect. 2.4	–	54729.3665	3	468064	Sect. 2.10	–
53289.4099	5	444473	Sect. 2.4	–	54729.4272	4	468065	Sect. 2.10	–
53292.4012	3	444522	Sect. 2.4	–	54730.2815	3	468079	Sect. 2.10	–
53304.3034	5	444717	Sect. 2.6	V	54730.3428	4	468080	Sect. 2.10	–
53304.3649	4	444718	Sect. 2.6	V	54730.4039	3	468081	Sect. 2.10	–
53306.3184	4	444750	Sect. 2.6	V	54730.4647	4	468082	Sect. 2.10	–
53307.2334	4	444765	Sect. 2.6	V	54734.3710	3	468146	Sect. 2.11	V
53307.2936	1	444766	Sect. 2.6	V	54734.4318	4	468147	Sect. 2.11	V
53307.3556	4	444767	Sect. 2.6	V	54736.3854	5	468179	Sect. 2.11	V
53307.4163	1	444768	Sect. 2.6	V	54738.3388	5	468211	Sect. 2.10	–
53309.3698	4	444800	Sect. 2.6	V	54738.3993	4	468212	Sect. 2.11	V
53311.3842	4	444833	Sect. 2.6	V	54738.3999	5	468212	Sect. 2.10	–
53334.9453	–	445219	DKB2009	I	54739.3754	5	468228	Sect. 2.11	V
53336.9592	–	445252	DKB2009	I	54749.3254	3	468391	Sect. 2.10	–
53337.9357	–	445268	DKB2009	I	54749.3867	4	468392	Sect. 2.10	–
53556.8802	4	448855	Sect. 2.7	B	54757.2605	5	468521	Sect. 2.10	–
53556.9409	4	448856	Sect. 2.7	B	54757.3214	4	468522	Sect. 2.10	–
53557.7959	5	448870	Sect. 2.7	B	54757.3825	5	468523	Sect. 2.10	–
53557.8567	5	448871	Sect. 2.7	B	54761.2892	5	468587	Sect. 2.10	V
53557.9178	5	448872	Sect. 2.7	B	54761.3503	5	468588	Sect. 2.10	V
53558.7723	5	448886	Sect. 2.7	B	54781.2485	3	468914	Sect. 2.10	V
53558.8336	5	448887	Sect. 2.7	B	54781.3091	2	468915	Sect. 2.10	V
53558.8945	5	448888	Sect. 2.7	B	54796.2637	5	469160	Sect. 2.10	V
53559.7489	5	448902	Sect. 2.7	B	54796.3253	5	469161	Sect. 2.10	V
53559.8101	5	448903	Sect. 2.7	B	54809.2041	5	469372	Sect. 2.10	V
53559.8709	5	448904	Sect. 2.7	B	54809.2648	5	469373	Sect. 2.10	V
53559.9320	5	448905	Sect. 2.7	B	54827.2105	4	469667	Sect. 2.10	V
53561.7632	5	448935	Sect. 2.7	–	55085.4631	1	473898	Sect. 2.11	R
53561.8244	5	448936	Sect. 2.7	–	55085.4633	1	473898	Sect. 2.11	V
53563.7774	5	448968	Sect. 2.7	B	55085.4641	1	473898	Sect. 2.11	B
53563.8387	5	448969	Sect. 2.7	B	55114.3956	1	474372	Sect. 2.11	V
53563.8997	5	448970	Sect. 2.7	B	55114.3957	1	474372	Sect. 2.11	R
53565.7310	4	449000	Sect. 2.7	B	55114.3964	1	474372	Sect. 2.11	B
53565.7919	5	449001	Sect. 2.7	B	55157.2436	1	475074	Sect. 2.11	B
53565.8526	4	449002	Sect. 2.7	B	55157.2449	2	475074	Sect. 2.11	V
53565.9138	5	449003	Sect. 2.7	B	55157.2452	1	475074	Sect. 2.11	R